Improved fab CDU with FlexRay and LithoTuner

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ABSTRACT

FlexRay programmable illumination and LithoTuner software is combined in several use cases. The first use case is optical proximity error (OPE) minimization. Simulation predicts the rms OPE error is reduced by 39% with LithoTuner and FlexRay, and is confirmed via experiment with a reduction of 33%. For minimizing the OPE error, two types of illumination tuning was performed, sigma tuning and freeform tuning. The sigma tuning is able to reduce the mean-to-target critical dimension (CD) error, but the CD error variance is unaffected. Freeform tuning, however, is able to reduce both the mean-to-target CD and the CD error variance. The second use case is matching two ArF scanners, a XT:1950Hi with FlexRay to a XT:1700Fi with diffractive optical element (DOE) illumination. With LithoTuner and FlexRay, simulation predicts the CD error post-matching is reduced by 51%, and experiment was able to achieve a reduction of 29%.

1. INTRODUCTION

As the technology node continues to shrink, there are three needs that holistic lithography fulfills. The first need is to create the largest process window (PW) possible. Using FlexRay [1] and Source Mask Optimization (SMO) [2,3,4] software, the largest possible window is realized. FlexRay uses a programmable illuminator in which the source intensity is created with a micro-mirror array. This micro-mirror array allows larger degrees of freedom in source shape creation compared to a completely refractive optical illuminator. The second need is to realize the largest PW on every scanner. Using FlexRay and LithoTuner software, Pattern Matcher Full Chip (PMFC) [5,6], the PW can be maintained on every scanner by matching the scanners in a production environment. By matching a population of scanners, the total CDU of the fab improves which leads to better device yield. Finally, the third need is to fix problems post tape-out once the process and mask is fixed. Typical post tape-out errors include hot spots from OPC errors or wafer CD error from mask making errors [7]. In the last use case, mean to target, across field, mask making errors are minimized through intrafield dose optimization with DoseMapper [8] combined with FlexRay source tuning to reduce the CDU using LithoTuner software. Using FlexRay and DoseMapper, OPC errors and mask making errors are correctable. In this paper, the second need of maintaining the PW on every scanner is discussed, and results are presented.

In Section 2.1, PMFC results are shown to match two ArF scanners. An ArF XT:1950Hi scanner with FlexRay is matched to an ArF XT:1700Fi scanner with a diffractive optical element (DOE). PMFC reduces the CDU by 33% for a 45nm half pitch layer (k1=0.28, NA=1.2). In Section 2.2, PMFC and FlexRay is also used to reduce the optical proximity error on the scanner. This optical proximity error could be from an OPC error, or a reticle manufacturing issue.

2. FlexRay use in LithoTuner Pattern Matcher Full Chip

LithoTuner with FlexRay maintains the process window on every scanner in a production environment. In this section, a 45nm half-pitch node layer (k1=0.28, NA=1.2) was exposed with a cQuad illumination. Two LithoTuner applications are used to reduce the rms CD error, and results are reported in this Section. The first application is matching a XT:1950Hi scanner with FlexRay illumination to a XT:1700Fi scanner with a diffractive optical element (DOE) illumination. The second application is reducing the optical proximity error (OPE) on XT:1950Hi with FlexRay illumination, and thereby reducing the CD error on wafer relative to target. In both use applications, the reduction of CD error is verified through wafer exposures at the Albany Nanotech facility.

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2.1 Scanner Matching

In the first application of matching XT:1950Hi FlexRay to XT:1700Fi DOE, the matching was performed with LithoTuner Pattern Matcher FullChip (PMFC). A reference model for cQuad illumination is created from wafer CD measurements on the XT:1950Hi. The reference model calibration serves the purpose of building the resist (empirical) part of the model, which is similar to the calibration of an OPC model. The reference model needs to be accurate for sensitivity predictions. From the reference model, the model sensitivity of wafer CD to changes in optical parameters is determined. These parameters include the NA, dose, and illumination. From the parameter sensitivity, a sub-recipe is created on the XT:1950Hi in which the FlexRay illumination, NA, and dose are tuned on the XT:1950Hi scanner to match the wafer CD on a XT:1700Fi with DOE. In order to match the XT:1950Hi to the XT:1700Fi, another model called the to-be-matched (TBM) model is created to determine the state of the to-be-matched scanner. In this case since the XT:1950Hi is matched to the XT:1700Fi, the TBM model is created for the 1950Hi. The resist model from reference model calibration is shared between reference model and the TBM model calibration as it is assumed that the resist processing conditions between the reference and TBM scanner are nominally the same. Similar to OPC model calibration, the reference model only needs to be calibrated once while the TBM model needs to be calibrated for every scanner in the fab. The TBM model gives the current status of the lithography cluster, and needs to be periodically updated. For the experiments used in this paper, the reference and TBM model is input to Tachyon PMFC to create a sub-recipe for the TBM XT:1950Hi scanner. After applying this sub-recipe, the XT:1950Hi scanner prints wafer CD results that are closer to the wafer CD results on the XT:1700Fi. This flow is shown in Figure 1.

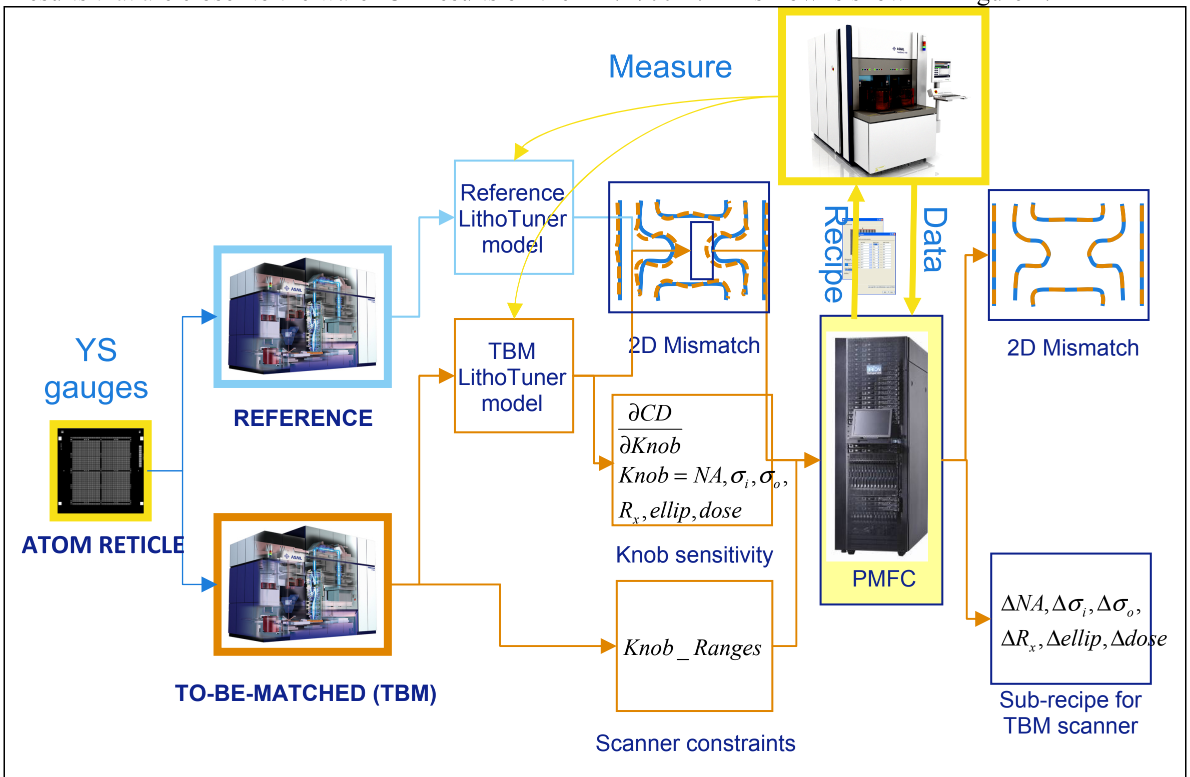

Figure 1. The flow for matching the XT:1950Hi to the XT:1700Fi is shown. The XT:1950Hi is the To-Be-Matched (TBM) scanner, and the reference scanner is the XT:1700Fi. By collecting experimental wafer CD data with YieldStar on the XT:1950Hi and XT:1700Fi, the reference model is created for the XT:1700Fi, and TBM model is created for the XT:1950Hi. This model is input to Tachyon PMFC to create a sub-recipe for the TBM XT:1950Hi scanner. After applying this sub-recipe, the XT:1950Hi scanner prints wafer CD results that are closer to the wafer CD results on the XT:1700Fi.

For FlexRay illumination there are two types of tunable illumination parameters. In one set of parameters, PMFC tuning is performed in which the illumination sigma-in and sigma-out are tuned to mimic the type of

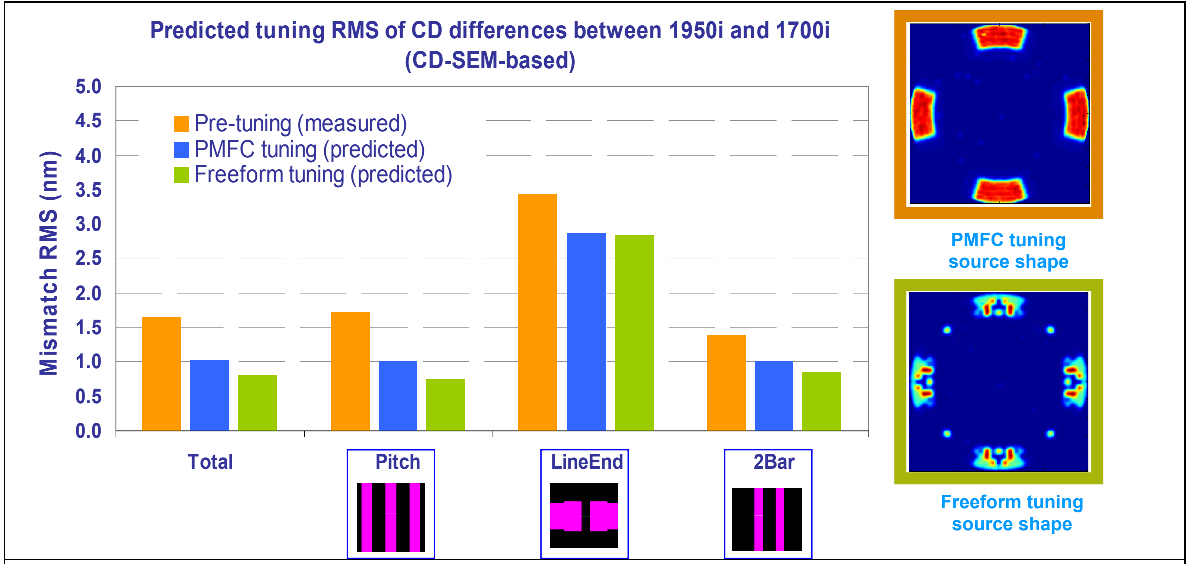

Figure 2. Simulation results of matching a XT:1950Hi scanner with FlexRay illumination to a XT:1700Fi scanner with a diffractive optical element (DOE) illumination for a 45nm half-pitch node (k1=0.28, NA=1.2). Two types of tuning were preformed PMFC tuning (sigma, NA, and dose tuning) and Freeform tuning (micro-mirror array on FlexRay, NA and dose tuning).

changes possible for DOE illumination. In the other set of parameters, the source is treated as a freeform source and more aggressive illumination changes are allowed, i.e., all the degrees of freedom offered by the micro-mirror array are used. In addition to tuning the illumination, the dose and NA was also optimized to reduce the rms CD error. The CD error results for both types of illumination changes are reported through simulation and verified through experiments with wafer exposure. In Figure 2, the simulated results are shown. The total rms CD mismatch prior to tuning is 1.66nm. This root-mean-square (rms) CD mismatch is reduced to 1.02nm with PMFC tuning, and is reduced to 0.81nm with freeform FlexRay tuning. The freeform FlexRay tuning reduces the rms CD mismatch by 51%. The CD mismatch decrease with both sigma tuning and freeform FlexRay tuning is occurring for all pattern types: LS (line-space), LE (line-end) and 2 Bar. It is important for all pattern types that the CD error is reduced in order to ensure that one pattern type is not sacrificed for reduction of other pattern types. For example, for LE, which is a critical parameter for gate, has 3.43nm CD error pre-tuning, but is reduced to 2.87nm and 2.84nm for PMFC tuning and for freeform FlexRay tuning, respectively.

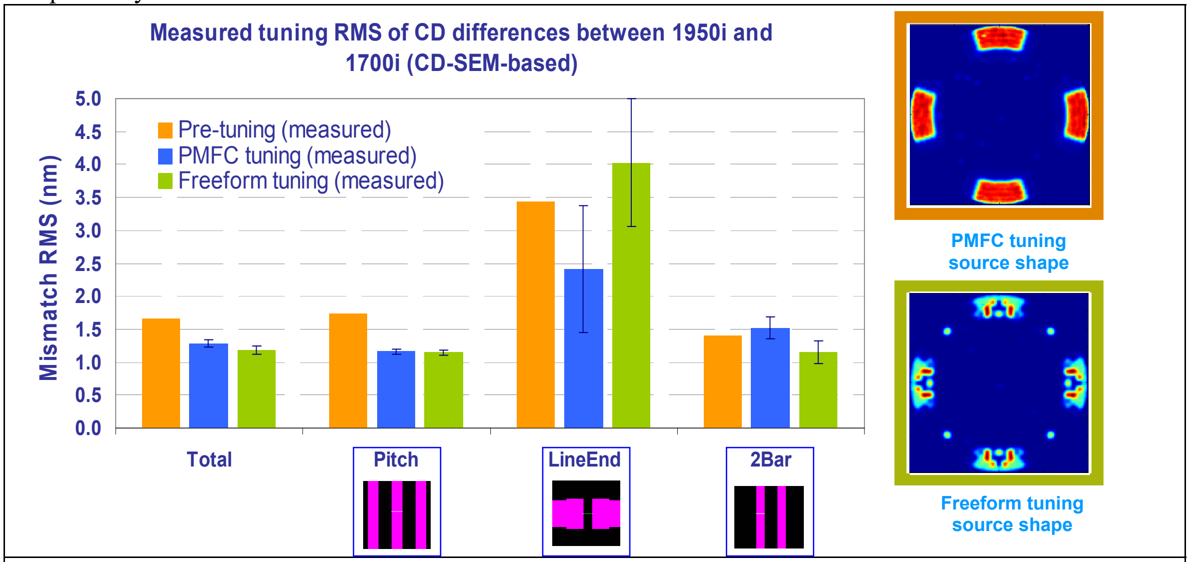

Figure 3. Experimental results of matching a XT:1950Hi scanner to XT:1700Fi scanner.

In Figure 3, the experimental CD error results are reported for sigma tuning and freeform tuning. The total rms CD error prior to tuning is 1.66nm. This rms CD error is reduced to 1.28nm with sigma-in and sigma-out tuning, and is reduced to 1.18nm with freeform FlexRay tuning. The freeform FlexRay tuning reduces the rms CD error by 29%. The full reduction of 51% predicted by simulation was not fully realized in the experimental results. The discrepancy is due to the large line end error (the error bar is ±1nm). The line end was very difficult to measure due to CD SEM metrology and process noise and due to the need to average over many features. The simulation is reporting a reduction of line end error from 3.43nm to 2.84nm (0.59nm reduction). For the reduction to be statistically significant the error bar in metrology needs to be less than 0.3nm. If the CD SEM has an line end error uncertainty of 1nm per measurement, 30 end of line measurements, n, need to be averaged for 95% confidence, $n=(\sigma_{SEM}\cdot z_{\alpha/2}/\sigma_{error\ bar})^2=(1\cdot 1.645/0.3)^2=30$. In the future, high precision YieldStar measurements will be used to create the models and verify the results. In Figure 4, the results in Figures 2 and 3 for CD error predicted by simulation and measured through experiment are reported for easier visualization between FlexRay tuning results and between freeform tuning results.

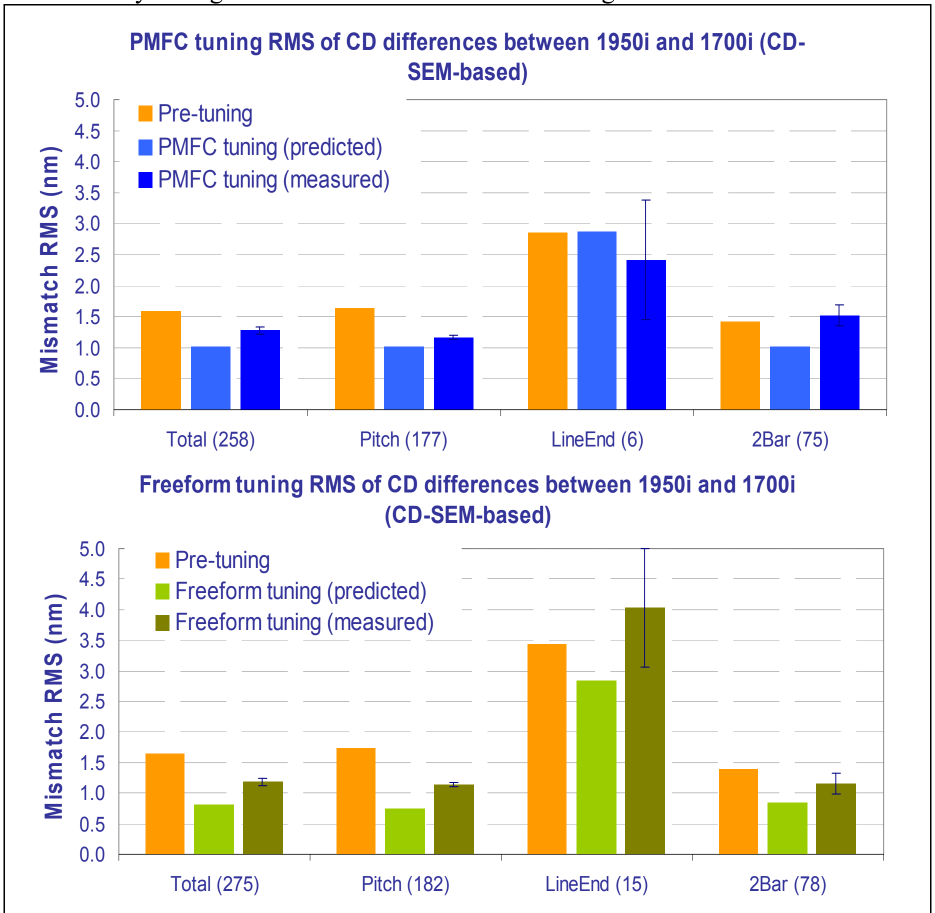

Figure 4. Experiment compared to simulated for matching a XT:1950Hi scanner to XT:1700Fi scanner.

The number of patterns that are required for the reference model and for the TBM model is reported in Table 1. In Table 1, 200 patterns are needed for creating the reference model. Similar to OPC model calibration, these 200 patterns include line space (LS), line ends, 2-bar, 3-bar structures and brick wall structures. The TBM model for PMFC tuning requires only 50 line space patterns. The TBM model (TCC-based) for freeform tuning requires 400 patterns which are both 1-D and 2-D. TCC-based uses the TCC (transmission cross coefficient) for matching the XT:1950Hi to the XT:1700Fi. The increase in TBM model patterns with freeform illumination is due to the increase in the degrees of freedom offered by FlexRay, in which each micro mirror position can be optimized. Lastly, the TBM model (TCC-based) is called TCC-based because the TCC is matched between two scanners rather than the CD. Specifically for the experiment above, the TCC of XT:1950Hi is matched to the TCC of XT:1700Fi. Matching of the TCC allows for the removal of metrology noise as the TCC is a slowing varying function which is less sensitive to metrology noise.

	Reference Model	TBM Model	TBM Model (TCC-based)
Total #patterns	**200**	**50**	**400**
L/S	100	50	100
2-Bar	30	0	40
3-Bar	20	0	100
Line Ends	30	0	20
Brick Wall	20	0	140

Table 1. Data required for building PMFC models. Note that the reference model and TBM model (TCC-based) requires 2-D patterns while the TBM Model does not require 2-D patterns.

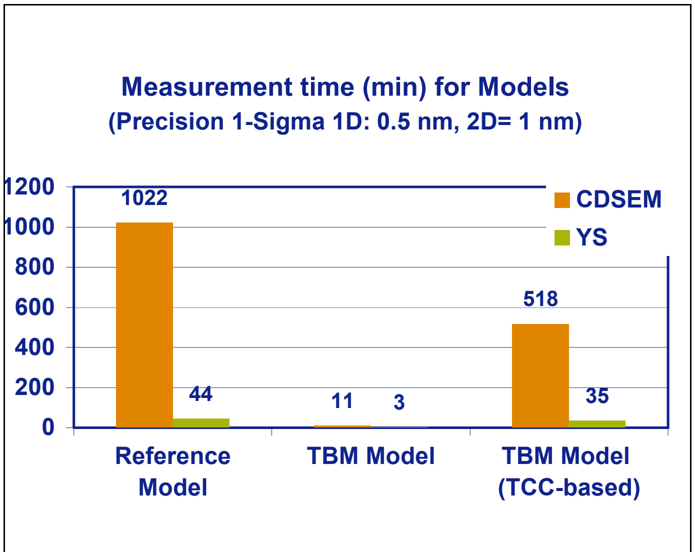

Figure 5. YieldStar and CD-SEM measurement time for acquiring data to build the PMFC models. The types of patterns to measure are reported in Table 1.

The patterns in Table 1 can be measured with two metrology tools, CD-SEM and YieldStar. Yieldstar is an optical scatterometry metrology tool. Since Yieldstar is an optical tool, Yieldstar measurement time is much faster than CD-SEM. In Figure 5, the measurement time for Yieldstar and CD-SEM is reported for acquiring data needed to calibrate the three models: Reference Model, TBM Model, and TBM Model (TCC-based). The most time consuming data acquisition is for the reference model because many 2-D measurements are needed with high precision. To achieve the precision for 2-D patterns, many fields are measured and averaged. For the reference model creation, the CD-SEM the data acquisition time is 1022 minutes versus 44 minutes for Yieldstar. Similar to the reference model, the TBM model (TCC-based) requires 2-D patterns as well. For the TBM model (TCC-based) the data acquisition time is 518 minutes for CD-SEM compared to 35 minutes with Yieldstar.

2.2 Optical proximity error (OPE) minimization

In the second use case, hotspots were reduced by using LithoTuner Design Hotspot Fix (DHF). The FlexRay illumination is tuned to fix hotspots from OPC errors or from reticle manufacture errors. On the XT:1950Hi, a reference model is created and possible design hotspots are detected by running a lithography manufacture check through Tachyon LMC. The FlexRay illumination is tuned to eliminate these hotspots. The elimination of hotspots are reported through simulation and verified with wafer exposure. In Figure 6, the simulated and experimental wafer optical proximity error (OPE) are reduced through FlexRay and LithoTuner. The OPE error is the residual error in the OPC which could be due to model calibration error or due to reticle manufacturing errors. With FlexRay and LithoTuner, it is possible to reduce this OPE once the reticle manufacturing is complete. In this case the TBM CD is the target CD in the design layout gds or oasis data.

Using the same exposure conditions as the XT:1950Hi to XT:1700Fi (NA=1.2, cQuad illumination), the OPE on the XT:1950Hi is minimized on 116 target 1-D patterns. Prior to tuning, the experimentally measured wafer CD OPE rms is

2.04nm. With PMFC sigma-in and sigma-out tuning, simulation predicts the OPE is reduced to 1.55nm. With freeform FlexRay tuning, simulation predicts the OPE is reduced to 1.25nm on the 116 target patterns. This is a reduction in rms OPE of 39% with freeform FlexRay tuning.

In Figure 6, the experimental results are also shown for sigma tuning and freeform FlexRay tuning. Before tuning, there is 2.04nm error between the printed CD and the target CD, OPE, for the 116 1-D patterns. Experiments show that PMFC tuning was not able to reduce the OPE significantly as the OPE was reduced from 2.04nm to 2.00nm. However, with freeform FlexRay tuning, the OPE is reduced to 1.36nm or a reduction of 0.68nm for a -33% change. The rms OPE is the cost function reduced. The rms OPE has two primary components: the change in mean CD error and the variance of the CD error. In order to better understand these components, the histogram is examined for the OPE CD error.

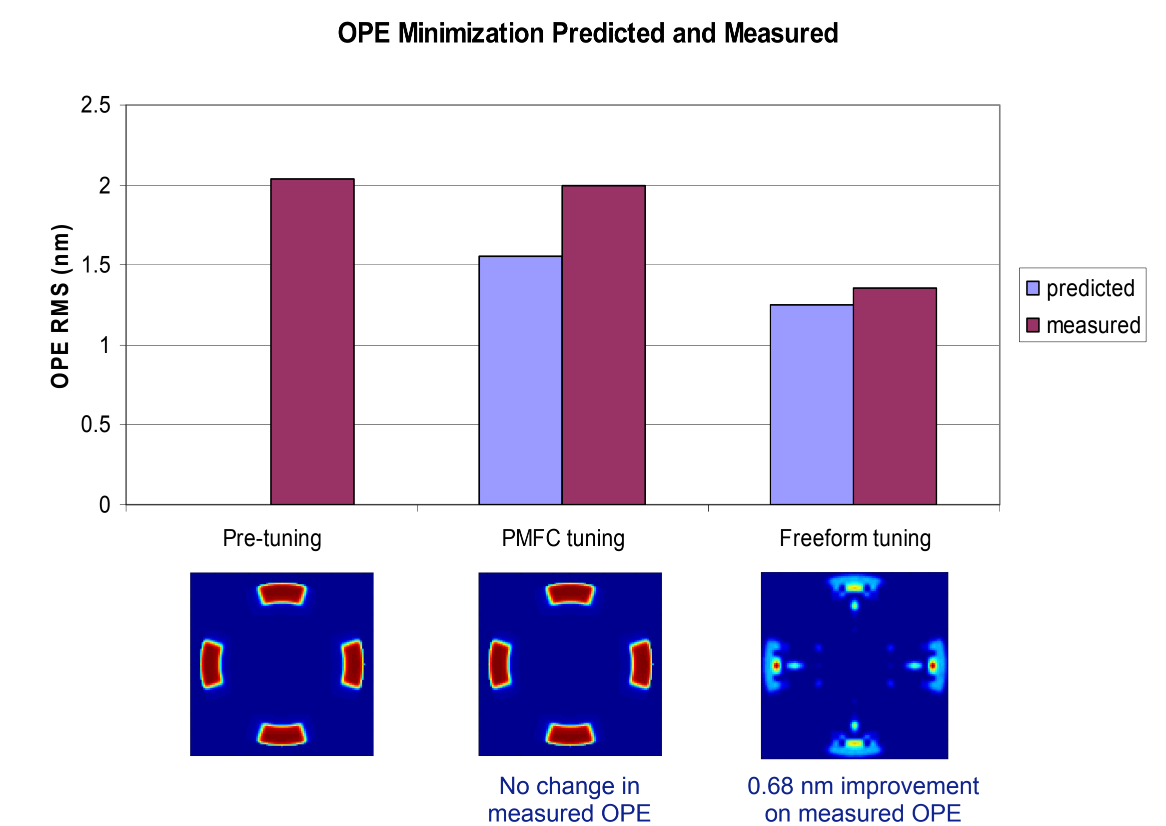

Figure 6. OPE minimization on the XT:1950Hi with experiment results compared to simulated results. Two types of tuning were preformed PMFC tuning (sigma, NA, and dose tuning) and Freeform tuning (micro-mirror array on FlexRay, NA and dose tuning).

In Figure 7, a histogram of simulated OPE errors as shown in Figure 6 is further expanded to determine the type of CD error reduction. It is important to remember the target CD for OPE minimization is the design target CD. Consequently, OPE minimization is trying to match wafer CD to design target CD. In matching wafer CD to target CD, there are two types of errors: mean-to-target CD error and CD variation error. In the histogram in Figure 7, both the mean-to-target errors and CD variation error are visible. The pre-tuning error has a mean centered at -1.68nm and a standard deviation of 1.55nm (see table 2). With PMFC regular tuning (sigma tuning), the mean-to-target error is reduced to 0.04nm as one can see that the histogram is centered around 0nm ΔCD. The sigma tuning, however, has the same CD error variation in the histogram as pre-tuning. For sigma tuning the standard deviation of the CD error is 1.71nm versus 1.55nm for pre-tuning. The freeform tuning simulation results, however, show that both mean-to-target CD and CD error variation is reduced by using all the degrees of freedom of FlexRay. In Figure 7, the freeform tuning reduces the mean-to-target CD error as the ΔCD is centered close to 0 while reducing the variation of the CD error. The freeform tuning reduces the mean-to-target CD error to 0.14nm while reducing the standard deviation to 0.45nm.

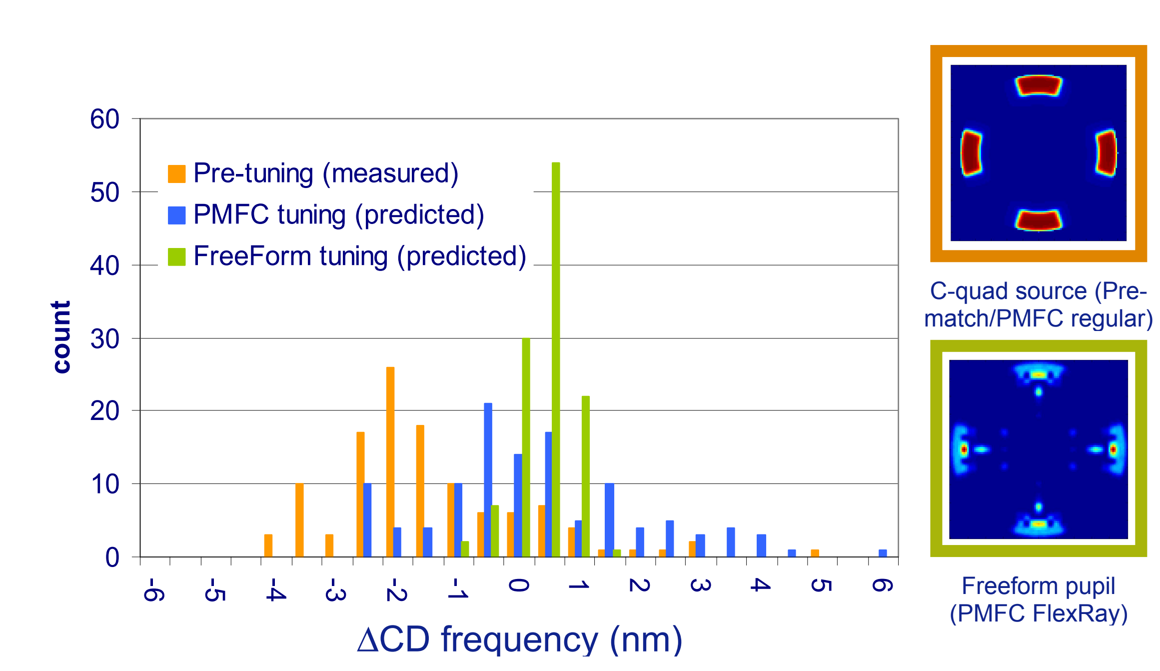

Figure 7. OPE minimization histogram for the simulated results. Note that PMFC tuning is capable of reducing the mean-to-target CD error, but PMFC tuning is not as effective as Freeform tuning to reduce the CD error variance.

In Figure 8, a histogram of experimental OPE errors as shown. The experimental results are similar to the simulation results. Similar to simulation, the experimental measured results show that PMFC tuning is capable of reducing the mean CD error (from -1.68nm to -0.32nm) while the PMFC freeform tuning results reduce both the mean CD error (from -1.68 to -0.10nm) and the standard deviation (from 1.55nm to 1.35nm). In general, the largest reduction in rms CD error is from the mean difference. If standard deviation reduction is primarily desired, it may be possible to use a different cost function such as a higher norm (such as 4 instead of 2) to emphasize reduction of the range of the CD error.

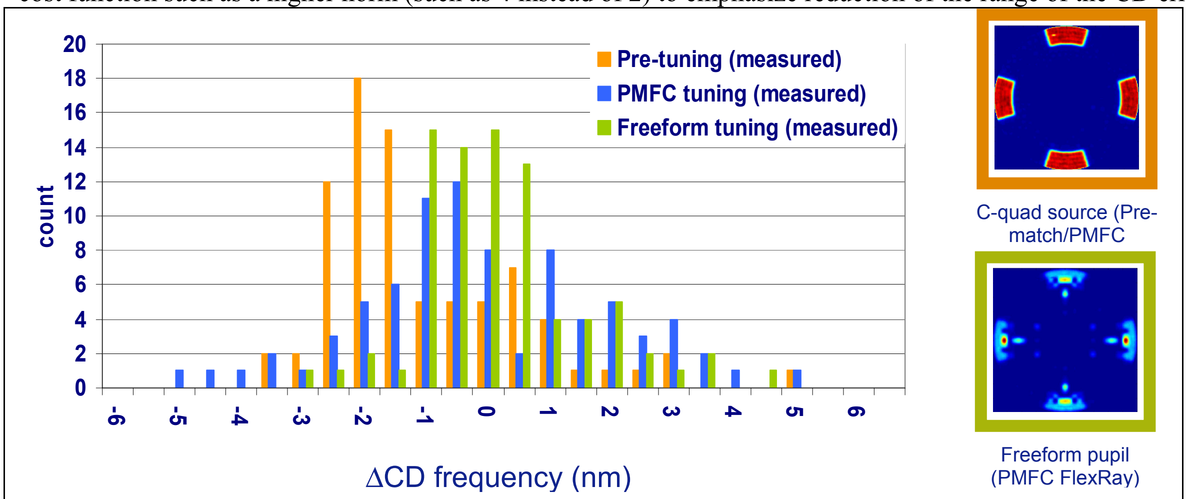

Figure 8. OPE minimization histogram for the experimental results.

	Pre-tuning	PMFC Regular tuning		PMFC Freeform Tuning	
	measured	predicted	measured	predicted	measured
mean	-1.68	0.04	-0.32	0.13	-0.10
stdev	1.55	1.71	1.97	0.45	1.35
range	8.94	8.63	10.11	2.28	7.78

Table 2. OPE minimization statistics in nanometers. Note that PMFC tuning is capable of reducing the mean-to-target CD error, but PMFC tuning is not as effective as Freeform tuning to reduce the CD error variance.

3. CONCLUSIONS

Holistic lithography in which the scanner is optimized through computational lithography allows the shrink to continue while maintaining the tightest wafer CD distribution. After SMO, LithoTuner realizes the better PW on every scanner in the production fab. Using LithoTuner, a XT:1950Hi scanner was matched to a XT:1700Fi scanner in which experiments confirmed the rms wafer CD error was reduced from 1.66nm to 1.18nm when using freeform FlexRay tuning. The combination of FlexRay and PMFC fixes problems in the post tape-out including OPC errors or mask making errors. A LithoTuner application in post tape-out was investigated. This application is reducing the optical proximity error (OPE) in which experiments confirmed the OPE was reduced from 2.04nm to 1.36nm when using freeform FlexRay tuning.

As the k1 becomes more aggressive, maximizing the process window during process creation is no longer sufficient. As the process is moved into volume production, this process window must be maintained to ensure the largest yield in the fab. In holistic lithography, the goal is to increase yield and maintain yield for the lifetime of the product design. With LithoTuner and FlexRay, the process window is maximized and the CDU is minimized. Since CDU is correlated to yield, the yield is maximized and is maintained for multiple scanners in the production fab.

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